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# RESEARCH MEMORANDUM

## EFFECT OF INLET OXYGEN CONCENTRATION ON COMBUSTION EFFICIENCY OF J33 SINGLE COMBUSTOR OPERATING WITH GASEOUS PROPANE

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RESEARCH MEMORANDUM

# EFFECT OF INLET OXYGEN CONCENTRATION ON COMBUSTION EFFICIENCY OF J33 SINGLE COMBUSTOR OPERATING WITH GASEOUS PROPANE

By Charles C. Graves

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## SUMMARY

An investigation was conducted to determine the effect of oxygen concentration of the inlet oxygen-nitrogen mixture on the combustion efficiency of a J33 single combustor operating with gaseous propane fuel. Combustion efficiency data were obtained at combustor-inlet total pressures from 10.0 to 30.0 inches of mercury absolute, fuel flow rates from 0.008 to 0.016 pound per second, and inlet oxygen concentrations from approximately 14 to 46 percent by volume. The combustor-inlet temperature and weight flow rate of the oxygen-nitrogen mixture were held constant at 40° F and 1.0 pound per second, respectively. Attempts were made to correlate combustion efficiency with selected fundamental combustion properties and with a simplified reaction kinetics equation. The results were compared with those obtained from a similar previous investigation conducted with liquid isooctane fuel.

At a given fuel flow rate, combustion efficiency obtained with propane increased with oxygen concentration. The rate of increase was appreciably greater at the lower oxygen concentrations and combustion efficiencies. Change in fuel flow rate had a small effect on combustion efficiency over the major portion of the conditions investigated. At a given fuel flow rate, satisfactory correlations were obtained between combustion efficiency and parameters based on (1) a simplified reaction kinetics equation and (2) a flame-speed mechanism. No satisfactory correlation was obtained between combustion efficiency and a parameter involving minimum spark-ignition energy. In a previous investigation in which liquid isooctane fuel was used, satisfactory correlations were obtained with all the parameters. For the same inlet conditions, the combustion efficiencies for the combustor operating with propane fuel were appreciably higher than those obtained for the combustor operating with isooctane fuel. The relative effects of inlet pressure and oxygen concentration on combustion efficiency were approximately the same for both fuels.

# INTRODUCTION

Research is being conducted at the NACA Lewis laboratory to study the relative importance of the basic processes involved in the over-all turbojet combustion mechanism. In a recent report (ref. 1) oxygen concentration of the inlet oxygen-nitrogen mixture was used as a combustor-inlet variable in an attempt to separate the molecular from the grosser scale processes and to relate changes in combustion efficiency to possible controlling individual processes in the over-all combustion mechanism. The combustion efficiency of a J33 single combustor operating 2800
with a liquid fuel (isooctane) was determined over a range of inlet pressures, oxygen concentrations, and fuel flow rates. The temperature and weight flow rate of the inlet oxygen-nitrogen mixture were held constant throughout the test program. At a constant fuel flow rate, combustion efficiency was related to selected fundamental combustion properties of vaporized isooctane-oxygen-nitrogen mixtures and to a simplified reaction kinetics equation. In this treatment of the combustion efficiency data, it was assumed that the fraction of the reaction zone required for the fuel evaporation and mixing steps was small and essentially constant with changes in inlet pressure and oxygen concentration.

Over the range of conditions investigated in reference 1, combustion efficiency increased with fuel flow rate. This effect might be tentatively attributed to the reduction in average drop size at the higher fuel pressures associated with the higher fuel flow rates, either in terms of reduction of fuel evaporation time or change in the fraction of the fuel deposited on the liner walls. Since the fuel evaporation step can have a significant effect on combustor performance, it would be desirable to determine the effect of this step on the correlations obtained in reference 1. A possible method would involve duplication of the tests of reference 1 with the fuel evaporation step eliminated through the use of a gaseous or vaporized fuel. Comparison of the two sets of data may indicate the effect of the fuel evaporation step on the applicability of the several correlations developed in reference 1.

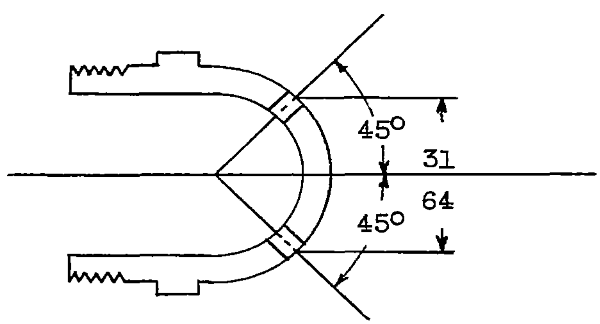
Considerable fundamental data were available for propane-oxygen-nitrogen mixtures. Accordingly, the combustion efficiency of a J33 single combustor operating with gaseous propane was determined over a range of inlet oxygen concentrations (approximately 14 to 46 percent by volume), inlet total pressures (10.0 to 30.0 in. Hg abs.), and fuel flow rates (0.008 to 0.016 lb/sec). The weight flow rate and inlet temperature of the oxygen-nitrogen mixture were held constant at 1.0 pound per second and 40° F, respectively. Attempts were made to correlate the combustion-efficiency data with selected fundamental combustion properties of propane-oxygen-nitrogen mixtures and a simplified reaction kinetics equation. The results are compared with those obtained for the J33 combustor operating with isooctane fuel (ref. 1).

## APPARATUS AND PROCEDURE

The single J33 combustor installation is shown diagrammatically in figure 1. The test facility was supplied with refrigerated air at 48 inches of mercury absolute and -40° F and was connected to the laboratory low-pressure exhaust system. The air flow and inlet pressure in the combustor were controlled by valves located upstream and downstream of the combustor. Combustor-inlet-air temperature was regulated by valves proportioning the amount of air passing through a steam-fed heat exchanger. Oxygen concentration was varied by metering quantities of pure oxygen or nitrogen into the inlet-air system. Air flow rates were measured by means of a square-edged orifice installed according to A.S.M.E. specifications and located upstream of the regulating valves; oxygen (or nitrogen) flow rates were measured by calibrated critical flow orifices. Additional details of the oxygen (or nitrogen) system are given in reference 1.

The fuel system was connected to the laboratory gaseous propane supply line (fig. 1). Propane flow rates were measured with a square-edged orifice installed according to A.S.M.E. specifications and located upstream of the flow-regulating valve. The propane orifice upstream temperature was controlled by a valve proportioning the amount of propane passing through a hot-water heat exchanger. Fuel-nozzle-discharge pressure was measured with a calibrated Bourdon gage. Commercially supplied propane (approximately 97 mole percent purity) was used throughout the program.

A cross-sectional view of the combustor is shown in figure 2. The hollow-cone spray nozzle used in reference 1 (45° cone angle, 10.5 gal/hr capacity) was replaced with the modified commercial hollow-cone spray nozzle tip illustrated below. The normal discharge orifice was blocked and the swirl chamber and retaining plug removed. Six $\frac{1}{16}$-inch diameter holes, equally spaced around the nozzle tip, were drilled at a 45° angle from the nozzle axis.



Cross-sectional views of the combustor instrument stations are also presented in figure 2. At each station the thermocouples and total-pressure tubes were located at the centers of equal annular areas. Design details of the total-pressure rakes and thermocouple rakes are presented in reference 2. Exhaust thermocouples with single cylindrical shields were connected in a parallel circuit to give an instantaneous average temperature reading. All thermocouples were connected through multiple switches to a dual-range, self-balancing potentiometer.

Combustion efficiency was determined at combustor-inlet total pressures of 10.0, 14.3, 21.4, and 30.0 inches of mercury absolute, inlet oxygen concentrations from approximately 14 to 46 percent by volume, and fuel flow rates of 0.008, 0.012, and 0.016 pound per second. The inlet temperature and weight flow rate of the oxygen-nitrogen mixture were held constant at 40° F and 1.0 pound per second, respectively. 2800

Combustion efficiency, defined as the ratio of the actual to the theoretical increase in enthalpy across the combustor, was computed by means of the equations and charts presented in reference 3. The enthalpy rise of the oxygen-nitrogen mixture was computed from enthalpy values of oxygen and nitrogen tabulated in reference 4. The combustor reference velocities presented herein were computed from the maximum cross-sectional area of the combustor flow passage (0.267 sq ft), the inlet oxygen-nitrogen mixture density, and the oxygen-nitrogen mixture flow rate. Indicated thermocouple readings were not corrected for radiation, conduction, or stagnation effects.

## RESULTS AND DISCUSSION

### Combustor Data

The data obtained in the investigation to determine the effect of inlet oxygen concentration on the combustion efficiency of a J33 combustor operating with propane fuel are presented in table I. In figure 3, combustion efficiency is plotted against inlet oxygen concentration (volume percent) at the various inlet pressures and fuel flow rates investigated. It is noted that combustion efficiency increased with inlet oxygen concentration and that the rate of increase was more pronounced at the lower values of oxygen concentration. Combustion efficiency increased with pressure, as would be expected.

The faired curves of figure 3 are combined in figure 4 to show the effect of fuel flow rate on combustion efficiency. Except at low values of oxygen concentration, fuel flow rate had a relatively small effect on combustion efficiency. Although no attempt was made to determine exact blow-out limits, it was observed that blow-out generally occurred at lower values of oxygen concentration with the lower fuel flow rates.

## Application of Fundamental Combustion Properties to Combustor Data

In reference 1 the variation in combustion efficiency with inlet pressure and oxygen concentration was related to minimum spark-ignition energy, quenching distance, and laminar flame speed of isooctane-oxygen-nitrogen mixtures. The same fundamental combustion properties were considered in the present investigation.

Minimum spark-ignition energy and quenching distance. - Curves of minimum spark-ignition energy and quenching distance for propane-oxygen-nitrogen mixtures at various fuel concentrations are presented in reference 5 for oxygen concentrations from 21 to 100 percent by volume and for total pressures from 0.2 to 1.0 atmosphere. There was no consistent relation between combustion efficiency and values of minimum spark-ignition energy obtained from reference 5 either at a stoichiometric fuel-oxygen ratio or at a fuel-oxygen ratio giving the lowest value of minimum spark-ignition energy at a given pressure and oxygen concentration. The inability to obtain a satisfactory correlation between minimum spark-ignition energy and combustion efficiency, as obtained in reference 1, possibly may be due to large errors arising from the cross-plotting and extrapolation required in the application of the data of reference 5 to the low oxygen concentrations tested in the present investigation. Since similar errors could arise in the use of the quenching distance data of reference 5, no attempt was made to relate combustion efficiency to quenching distance.

Laminar flame speed. - In reference 1 a parameter based on a flame-speed mechanism was derived which satisfactorily correlated the effect of inlet pressure and oxygen concentration on combustion efficiency for the conditions of constant inlet temperature and weight flow rate of the oxygen-nitrogen mixture. This relation is of the form

$$\eta_b = f\left(\frac{P_i^{1/3}\, u_f}{V_r}\right) \qquad (1)$$

where

$\eta_b$ combustion efficiency

$P_i$ combustor-inlet pressure

$u_f$ laminar flame speed based on combustor-inlet conditions

$V_r$ reference velocity

Equation (1) was applied to the data of reference 1 by assuming laminar flame speed to be independent of pressure and by using the results of reference 6 in which the maximum flame speed of isooctane-oxygen-nitrogen mixtures was found to be proportional to the term $(\alpha - 12)$. Here $\alpha$ is the volume percent inlet oxygen concentration and the maximum flame speed is defined as the maximum point of the curve of flame speed against equivalence ratio at a given temperature and oxygen concentration. The resulting correlation equation was

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$$\eta_b = f\left[\frac{P_i^{1/3}}{V_r}(\alpha - 12)\right] \tag{2}$$

In reference 7 the flame speeds of propane-oxygen-nitrogen mixtures at atmospheric pressure and various equivalence ratios were determined for laminar Bunsen flames by the area method. Flame speeds were measured for oxygen concentrations from 16.6 to 49.6 percent by volume and for inlet temperatures of $311^\circ$ and $422^\circ$ K. The effect of inlet temperature and oxygen concentration on maximum flame speed for the entire range of conditions investigated was correlated by the relation

$$u_f = KT_i^a(\alpha - b) \tag{3}$$

where K, a, and b are constants and $T_i$ is the inlet temperature. A similar correlation was applied to the data of reference 7 for oxygen concentrations of 30 percent by volume and below in order to provide a more accurate representation of the flame speeds at the low oxygen concentrations used in the present investigation. For this range the constant b in equation 3 has an average value of 11.5. It is noted that this value of b, which represents the extrapolated value of oxygen concentration for zero flame speed, is in agreement with the value of 11.6 cited in reference 8 (pp. 58-59) as the oxygen concentration below which no propane-oxygen-nitrogen mixture can propagate flame at room temperature and pressure. For constant inlet temperature $T_i$, the maximum flame speed of propane is proportional to the term $(\alpha - 11.5)$. Thus, if the laminar flame speed is assumed independent of pressure, equation (1) becomes

$$\eta_b = f\left[\frac{P_i^{1/3}}{V_r}(\alpha - 11.5)\right] \tag{4}$$

for propane combustion.

In figure 5 combustion efficiency is plotted against the parameter of equation (4) for the three fuel flow rates investigated. It is seen that the parameter of equation (4) satisfactorily correlates the combustion-efficiency data of figure 3. However, there is some increase in scatter in the data at the low values of combustion efficiency with the fuel flow rate of 0.008 pound per second. It is noted that this parameter is approximately the same as that used to correlate the combustion-efficiency data of reference 1.

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Application of Simplified Reaction Kinetics Equation

to Combustor Data

In reference 1, the combustion efficiency data at a given fuel flow rate were also correlated by a simplified reaction kinetics equation given by

$$\eta_b = f\left[\frac{\alpha P_i\, T_i}{V_r}\left(\frac{e^{-E/RT_{eq}}}{T_{eq}^{3/2}}\right)\right] \tag{4}$$

where

E apparent energy of activation

R gas constant

$T_{eq}$ stoichiometric adiabatic equilibrium temperature

Details of the derivation and assumptions involved in the application of this equation to turbojet combustor data are presented in references 1 and 9. The equilibrium temperatures at the various oxygen concentration and pressures covered in this investigation were computed according to the methods and charts of reference 10. Values of $E$ were obtained from cross plots of the faired curves of figure 3 by determining the slope of the best straight line through the plotted points of $1/T_{eq}$ against

$$\ln\left(\frac{T_{eq}^{-3/2}\,\alpha P_i\, T_i}{V_r}\right)$$

at a constant value of combustion efficiency. The values of $E$ determined by this method varied from approximately 27,000 calories per gram-mole in the low combustion-efficiency range to approximately

33,000 calories per gram-mole in the high combustion-efficiency range. Since the slope of the curve of

$$\frac{\alpha P_i\ T_i}{V_r}\left(\frac{e^{-E/RT_{eq}}}{T_{eq}{}^{3/2}}\right)$$

against combustion efficiency is quite steep in the low combustion-efficiency range, the scatter of the correlation in this range will be very sensitive to the choice of $E$. In figure 6 the data of table I are plotted against the reciprocal of the combustion efficiency parameter of equation (4) for a value of $E/R$ of $14,000^\circ$ K ($E = 27,818$ cal/g mole). This choice of $E$ results in a satisfactory correlation of the combustion data. Use of a higher value of $E$ would result in some decrease in scatter of the correlation at the higher values of combustion efficiency and an appreciable increase in scatter of the correlation at the low values of combustion efficiency. However, in view of the sensitivity of the correlation parameter at the low efficiency range to the accuracy of the measurement of combustor-inlet oxygen concentration, determination of an exact value of $E$ between 27,000 and 33,000 calories per gram-mole for a minimum scatter of the correlation was not warranted. The range of values of $E$ is in reasonable agreement with those cited for propane in the literature. In reference 11 a value of 38,000 calories per gram-mole is given. This value was used in reference 7 in the application of the Semenov thermal theory of flame propagation to the flame speed data of propane-oxygen-nitrogen mixtures. Unpublished observations by the authors of reference 7 indicated that a value of 34,000 calories per gram-mole resulted in an improvement between experimental and predicted values of flame speed.

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## Comparison of Liquid and Gaseous Fuel Data

In reference 1, similar data were obtained with liquid isooctane fuel for the same combustor but a different fuel-injection nozzle. Comparisons of the combustion efficiencies obtained with propane and with isooctane, for the same operating conditions, are presented in figure 7. Over the entire range of conditions compared, the combustion efficiencies obtained with propane were appreciably higher than those obtained with isooctane; the differences were more pronounced at the lower oxygen concentrations. The relative effects of inlet oxygen concentration and pressure on combustion efficiency, however, were approximately the same for both fuels.

Combustion efficiency increased with fuel flow rate for isooctane. This trend would be expected as a result of the smaller average fuel-spray drop size and hence decreased evaporation time at the higher fuel flow rates. With propane, no evaporation step was required, and fuel flow rate had a small effect on combustion efficiency over the major portion of conditions investigated (fig. 4).

A correlation between combustion efficiency and minimum spark-ignition energy, such as was found in reference 1 with liquid isooctane, was not obtained with propane. The simplified reaction kinetics equation parameter and flame-speed parameter correlated the data obtained for both propane and isooctane. The values of the apparent energy of activation required in the second-order reaction equation parameter were in reasonable agreement with those expected for the two fuels.

The data obtained in these investigations also indicate that the reduction in combustor-inlet oxygen concentration resulting from the use of supply air heated by the addition of exhaust gases may result in an appreciable lowering of combustion efficiency.

### Limitations of Correlation Parameters

The relative effects of inlet pressure and velocity on combustion efficiency predicted by the flame speed parameter differ appreciably from those predicted by the second-order reaction equation parameter. In the present investigation, conducted at constant weight flow rate of the oxygen-nitrogen mixture, it was not possible to determine relative effects of inlet pressure and velocity on combustion efficiency and, hence, to distinguish between parameters. Determination of the ability of either parameter to correlate combustion efficiency at conditions other than those investigated will require additional tests involving independent variation of combustor-inlet pressure, temperature, velocity, and fuel flow.

## SUMMARY OF RESULTS

The following results were obtained from an investigation of the effect of inlet oxygen concentration on the combustion efficiency of a J33 combustor operating with gaseous propane fuel and from comparison with data from a previous similar investigation conducted with liquid isooctane fuel:

1. At a given fuel flow rate, combustion efficiency increased with oxygen concentration; the rate of increase was appreciably greater at the lower oxygen concentrations and combustion efficiencies. Variations in fuel flow rate had a small effect on combustion efficiency at most conditions investigated.

2. At a given fuel flow rate, satisfactory correlations between combustion efficiency and minimum spark-ignition energy, laminar flame speed, or a simplified reaction kinetics equation were obtained in a previous investigation conducted with liquid isooctane; however, with gaseous propane fuel a satisfactory correlation was obtained only with the simplified reaction kinetics equation and flame-speed parameter.

3. For the same inlet conditions, combustion efficiencies obtained with propane were appreciably higher than those obtained with isooctane; the relative effects of pressure and oxygen concentration on combustion efficiency were approximately the same for both fuels.

4. The reduced oxygen concentration of combustion-inlet air resulting from the use of supply air heated by the addition of exhaust gases may result in appreciable lowering in combustion efficiency obtained with gaseous propane or liquid isooctane fuel. 2800

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TABLE I. - PERFORMANCE DATA FOR J33 SINGLE COMBUSTOR OPERATING WITH PROPANE

(a) Fuel flow rate, 0.008 pound per second

| Point | Combustor inlet total pressure, $P_1$, in. Hg abs | Combustor inlet temperature, $T_1$, °R | Combustor inlet oxygen-nitrogen mixture flow, lb/sec | Combustor inlet oxygen concentration, $\alpha$ vol. percent | Combustor reference velocity $V_r$, ft/sec | Fuel flow, lb/sec | Fuel-nozzle pressure drop, lb/sq in. | Mean combustor outlet temperature, °R | Mean temperature rise through combustor, °F | Combustion efficiency, percent |
|---|---|---|---|---|---|---|---|---|---|---|
| 52 | 10.0 | 502 | 1.01 | 20.1 | 144 | 0.0081 | 13.2 | 732 | 230 | 35.5 |
| 39 | 10.0 | 495 | 1.00 | 20.9 | 141 | .0080 | 12.8 | 790 | 295 | 45.6 |
| 3 | 10.0 | 498 | 1.00 | 20.9 | 141 | .0080 | 12.8 | 800 | 302 | 46.2 |
| 64 | 10.0 | 499 | 1.00 | 20.9 | 142 | .0081 | 13.3 | 795 | 296 | 45.5 |
| 46 | 10.0 | 502 | 1.00 | 24.2 | 142 | .0081 | 13.5 | 960 | 458 | 70.7 |
| 166 | 10.0 | 500 | 1.00 | 24.2 | 141 | .0080 | 12.9 | 945 | 445 | 69.4 |
| 161 | 10.0 | 499 | 1.00 | 25.1 | 141 | .0080 | 12.9 | 970 | 471 | 73.5 |
| 141 | 10.0 | 500 | 1.00 | 26.0 | 142 | .0080 | 12.9 | 995 | 495 | 77.0 |
| 155 | 10.0 | 500 | 1.00 | 26.0 | 141 | .0081 | 13.2 | 1005 | 505 | 78.4 |
| 40 | 10.0 | 500 | 1.00 | 26.2 | 141 | .0080 | 12.8 | 1002 | 502 | 78.0 |
| 34 | 10.0 | 504 | 1.00 | 28.4 | 142 | .0081 | 13.1 | 1050 | 546 | 84.7 |
| 37 | 10.0 | 502 | 1.01 | 28.4 | 142 | .0080 | 13.3 | 1047 | 545 | 85.0 |
| 142 | 10.0 | 502 | 1.00 | 30.0 | 141 | .0080 | 13.2 | 1070 | 568 | 88.3 |
| 31 | 10.0 | 503 | 1.01 | 30.4 | 142 | .0081 | 13.3 | 1065 | 562 | 87.3 |
| 28 | 10.0 | 503 | 1.01 | 32.5 | 142 | .0081 | 13.3 | 1075 | 572 | 88.9 |
| 22 | 10.0 | 503 | 1.00 | 46.3 | 138 | .0081 | 13.3 | 1140 | 637 | 97.7 |
| 117 | 14.4 | 500 | 1.00 | 18.2 | 99 | .0081 | 11.1 | 935 | 435 | 67.3 |
| 131 | 14.3 | 502 | 1.00 | 18.6 | 100 | .0080 | 11.1 | 962 | 460 | 72.1 |
| 119 | 14.3 | 500 | 1.00 | 19.2 | 99 | .0081 | 11.3 | 985 | 485 | 74.8 |
| 126 | 14.3 | 502 | 1.00 | 20.1 | 100 | .0080 | 10.8 | 1010 | 508 | 79.9 |
| 114 | 14.3 | 499 | 1.00 | 20.9 | 99 | .0080 | 11.0 | 1018 | 519 | 81.0 |
| 105 | 14.2 | 502 | 1.01 | 20.9 | 101 | .0081 | 11.2 | 1013 | 511 | 80.1 |
| 121 | 14.3 | 499 | 1.00 | 20.9 | 99 | .0080 | 11.1 | 1018 | 519 | 81.0 |
| 147 | 14.3 | 498 | 1.00 | 20.9 | 99 | .0080 | 11.1 | 1020 | 522 | 81.6 |
| 132 | 14.3 | 501 | 1.00 | 24.2 | 99 | .0080 | 11.1 | 1075 | 574 | 90.1 |
| 167 | 14.3 | 500 | 1.00 | 24.2 | 99 | .0080 | 10.8 | 1070 | 570 | 89.5 |
| 160 | 14.3 | 500 | 1.01 | 25.0 | 99 | .0080 | 10.8 | 1075 | 575 | 90.8 |
| 138 | 14.3 | 502 | 1.00 | 26.0 | 99 | .0080 | 11.1 | 1110 | 608 | 95.7 |
| 154 | 14.3 | 500 | 1.00 | 26.0 | 98 | .0080 | 11.1 | 1100 | 600 | 93.8 |
| 112 | 14.3 | 500 | 1.00 | 28.0 | 98 | .0081 | 10.8 | 1117 | 617 | 95.9 |
| 109 | 14.3 | 506 | 1.00 | 30.2 | 99 | .0081 | 10.8 | 1130 | 624 | 96.7 |
| 106 | 14.3 | 504 | 1.00 | 32.2 | 98 | .0081 | 11.3 | 1130 | 626 | 97.2 |
| 104 | 21.3 | 504 | .99 | 14.2 | 67 | .0080 | 8.3 | 840 | 336 | 51.8 |
| 103 | 21.5 | 504 | 1.00 | 14.4 | 67 | .0080 | 8.2 | 855 | 351 | 54.6 |
| 76 | 21.5 | 497 | 1.00 | 15.1 | 66 | .0082 | 8.3 | 917 | 420 | 64.6 |
| 75 | 21.4 | 500 | .99 | 15.2 | 66 | .0081 | 8.1 | 908 | 408 | 62.7 |
| 86 | 21.5 | 501 | 1.00 | 16.2 | 67 | .0081 | 8.2 | 982 | 481 | 74.7 |
| 98 | 21.4 | 502 | 1.00 | 17.3 | 67 | .0081 | 8.3 | 1045 | 543 | 84.5 |
| 61 | 21.4 | 504 | 1.01 | 18.2 | 67 | .0081 | 8.0 | 1072 | 568 | 89.0 |
| 90 | 21.3 | 505 | 1.00 | 18.2 | 68 | .0082 | 8.3 | 1075 | 570 | 88.5 |
| 53 | 21.4 | 502 | 1.02 | 20.1 | 68 | .0081 | 8.0 | 1077 | 575 | 91.0 |
| 49 | 21.4 | 502 | 1.00 | 20.9 | 67 | .0082 | 8.3 | 1095 | 593 | 91.7 |
| 65 | 21.4 | 498 | 1.00 | 20.9 | 66 | .0081 | 7.9 | 1098 | 600 | 93.7 |
| 78 | 21.5 | 502 | 1.00 | 20.9 | 66 | .0081 | 8.0 | 1102 | 600 | 93.4 |
| 87 | 21.4 | 503 | 1.00 | 20.9 | 67 | .0082 | 8.1 | 1105 | 602 | 92.9 |
| 113 | 21.4 | 496 | 1.00 | 20.9 | 66 | .0080 | 7.8 | 1095 | 599 | 93.8 |
| 43 | 21.5 | 500 | 1.01 | 26.3 | 66 | .0081 | 8.1 | 1125 | 625 | 97.6 |
| 73 | 30.0 | 498 | 1.00 | 14.3 | 48 | .0081 | 6.4 | 925 | 427 | 66.3 |
| 71 | 30.1 | 500 | 1.00 | 15.3 | 47 | .0080 | 6.0 | 1027 | 527 | 83.3 |
| 84 | 30.0 | 501 | 1.00 | 16.2 | 48 | .0081 | 6.2 | 1058 | 557 | 87.3 |
| 96 | 30.0 | 503 | 1.00 | 17.2 | 48 | .0081 | 5.5 | 1095 | 592 | 91.7 |
| 93 | 30.1 | 500 | 1.00 | 18.2 | 47 | .0081 | 6.0 | 1110 | 610 | 95.0 |
| 59 | 30.2 | 505 | 1.00 | 19.2 | 48 | .0081 | 6.2 | 1130 | 625 | 98.3 |
| 58 | 30.1 | 503 | 1.02 | 20.1 | 48 | .0081 | 6.3 | 1125 | 622 | 99.1 |
| 13 | 30.1 | 502 | .99 | 20.9 | 47 | .0081 | 5.9 | 1135 | 633 | 98.1 |
| 70 | 30.0 | 497 | 1.00 | 20.9 | 47 | .0081 | 7.0 | 1135 | 638 | 99.9 |

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TABLE I. - PERFORMANCE DATA FOR J33 SINGLE COMBUSTOR OPERATING WITH PROPANE - Continued

(b) Fuel flow rate, 0.012 pound per second

| Point | Combustor inlet total pressure, $P_1$, in. Hg abs | Combustor inlet temperature, $T_1$, °R | Combustor inlet oxygen-nitrogen mixture flow, lb/sec | Combustor inlet oxygen concentration, α vol. percent | Combustor reference velocity $V_r$, ft/sec | Fuel flow, lb/sec | Fuel-nozzle pressure drop, lb/sq in. | Mean combustor outlet temperature, °R | Mean temperature rise through combustor, °F | Combustion efficiency, percent |
|---|---|---|---|---|---|---|---|---|---|---|
| 47 | 10.0 | 502 | 1.00 | 24.3 | 142 | 0.0121 | 22.1 | 1137 | 635 | 66.8 |
| 163 | 10.0 | 501 | 1.01 | 25.1 | 142 | .0120 | 21.9 | 1183 | 682 | 73.0 |
| 145 | 10.0 | 502 | 1.00 | 26.0 | 142 | .0119 | 21.9 | 1242 | 740 | 79.7 |
| 156 | 10.1 | 500 | 1.00 | 26.0 | 140 | .0119 | 21.7 | 1235 | 735 | 78.7 |
| 41 | 10.1 | 500 | 1.01 | 26.4 | 141 | .0120 | 22.0 | 1243 | 743 | 79.4 |
| 38 | 10.0 | 503 | 1.00 | 28.4 | 142 | .0121 | 22.3 | 1295 | 792 | 84.1 |
| 35 | 10.0 | 503 | 1.01 | 28.7 | 142 | .0120 | 22.1 | 1293 | 790 | 84.5 |
| 143 | 10.0 | 502 | 1.00 | 30.0 | 141 | .0119 | 21.8 | 1325 | 823 | 88.4 |
| 32 | 10.0 | 502 | 1.01 | 30.7 | 143 | .0120 | 22.1 | 1305 | 803 | 86.4 |
| 29 | 10.0 | 501 | 1.01 | 32.8 | 142 | .0121 | 22.3 | 1337 | 836 | 89.3 |
| 26 | 10.1 | 502 | 1.01 | 35.9 | 139 | .0121 | 22.1 | 1367 | 865 | 91.8 |
| 23 | 10.0 | 500 | 1.01 | 46.2 | 139 | .0120 | 22.1 | 1385 | 885 | 94.8 |
| 118 | 14.3 | 500 | 1.00 | 18.1 | 100 | .0120 | 19.8 | 1120 | 620 | 65.9 |
| 130 | 14.3 | 502 | 1.00 | 18.7 | 100 | .0119 | 20.1 | 1162 | 660 | 70.6 |
| 120 | 14.3 | 500 | 1.01 | 19.2 | 100 | .0120 | 19.8 | 1195 | 695 | 74.2 |
| 127 | 14.3 | 500 | 1.00 | 20.1 | 99 | .0119 | 19.8 | 1247 | 747 | 80.3 |
| 122 | 14.3 | 498 | 1.00 | 20.9 | 99 | .0119 | 19.8 | 1268 | 770 | 83.0 |
| 115 | 14.4 | 500 | 1.00 | 20.9 | 99 | .0120 | 19.6 | 1272 | 772 | 83.2 |
| 133 | 14.3 | 502 | 1.00 | 24.2 | 100 | .0119 | 19.8 | 1340 | 838 | 91.0 |
| 168 | 14.3 | 501 | 1.00 | 24.2 | 99 | .0119 | 19.8 | 1345 | 844 | 91.2 |
| 169 | 14.3 | 501 | 1.00 | 24.2 | 99 | .0119 | 19.8 | 1352 | 851 | 91.9 |
| 134 | 14.3 | 502 | 1.00 | 24.3 | 99 | .0119 | 19.8 | 1350 | 848 | 91.9 |
| 162 | 14.4 | 500 | 1.00 | 25.1 | 98 | .0119 | 19.8 | 1355 | 855 | 92.5 |
| 139 | 14.4 | 502 | 1.00 | 26.1 | 98 | .0119 | 19.8 | 1385 | 883 | 95.1 |
| 157 | 14.3 | 500 | .99 | 26.1 | 98 | .0119 | 19.6 | 1373 | 873 | 93.8 |
| 136 | 14.4 | 503 | 1.01 | 28.1 | 99 | .0119 | 19.8 | 1393 | 890 | 96.6 |
| 110 | 14.3 | 500 | 1.00 | 30.2 | 98 | .0120 | 19.8 | 1400 | 900 | 96.6 |
| 107 | 14.3 | 504 | 1.00 | 32.3 | 99 | .0120 | 19.8 | 1405 | 901 | 96.7 |
| 77 | 21.4 | 495 | 1.00 | 15.1 | 66 | .0122 | 16.6 | 1103 | 608 | 64.0 |
| 97 | 21.5 | 502 | 1.00 | 16.3 | 66 | .0120 | 16.7 | 1265 | 763 | 81.6 |
| 83 | 21.4 | 506 | 1.01 | 17.2 | 68 | .0121 | 16.6 | 1310 | 804 | 86.4 |
| 62 | 21.5 | 503 | 1.01 | 18.1 | 67 | .0120 | 16.2 | 1350 | 847 | 91.8 |
| 91 | 21.4 | 503 | 1.01 | 18.2 | 67 | .0121 | 16.8 | 1345 | 842 | 90.3 |
| 54 | 21.4 | 502 | 1.02 | 20.0 | 68 | .0120 | 16.6 | 1360 | 858 | 94.0 |
| 50 | 21.5 | 502 | 1.01 | 20.9 | 67 | .0121 | 16.7 | 1390 | 888 | 95.3 |
| 66 | 21.4 | 498 | 1.01 | 20.9 | 66 | .0120 | 16.5 | 1385 | 887 | 95.9 |
| 88 | 21.4 | 502 | 1.00 | 20.9 | 67 | .0121 | 17.0 | 1395 | 893 | 95.6 |
| 44 | 21.4 | 501 | 1.01 | 26.3 | 67 | .0121 | 16.7 | 1412 | 911 | 98.2 |
| 72 | 29.9 | 500 | 1.00 | 15.2 | 48 | .0120 | 12.9 | 1275 | 775 | 83.6 |
| 85 | 30.1 | 502 | 1.00 | 16.2 | 48 | .0121 | 12.5 | 1345 | 843 | 90.7 |
| 99 | 30.0 | 502 | 1.00 | 17.2 | 48 | .0120 | 13.0 | 1400 | 898 | 96.7 |
| 94 | 30.1 | 501 | 1.00 | 18.1 | 48 | .0121 | 13.0 | 1407 | 906 | 97.5 |
| 60 | 30.1 | 505 | 1.00 | 19.1 | 48 | .0120 | 11.5 | 1427 | 922 | 99.1 |
| 57 | 30.1 | 504 | 1.02 | 20.1 | 48 | .0121 | 13.5 | 1420 | 916 | 100.3 |
| 15 | 30.1 | 503 | 1.00 | 20.9 | 47 | .0121 | 12.9 | 1430 | 927 | 99.1 |
| 69 | 30.0 | 498 | 1.00 | 20.9 | 47 | .0120 | 13.5 | 1427 | 929 | 100.2 |

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TABLE I. - PERFORMANCE DATA FOR J33 SINGLE COMBUSTOR OPERATING WITH PROPANE- Concluded

(c) Fuel flow rate, 0.016 pound per second

| Point | Combustor inlet total pressure, $P_1$, in. Hg abs | Combustor inlet temperature, $T_1$, °R | Combustor inlet oxygen-nitrogen mixture flow, lb/sec | Combustor inlet oxygen concentration, α vol. percent | Combustor reference velocity $V_r$, ft/sec | Fuel flow, lb/sec | Fuel-nozzle pressure drop, lb/sq in. | Mean combustor outlet temperature, °R | Mean temperature rise through combustor, °F | Combustion efficiency, percent |
|---|---|---|---|---|---|---|---|---|---|---|
| 48 | 10.0 | 501 | 1.00 | 24.3 | 142 | 0.0161 | 31.1 | 1205 | 704 | 56.4 |
| 164 | 10.0 | 501 | 1.01 | 25.0 | 143 | .0158 | 30.4 | 1290 | 789 | 65.2 |
| 146 | 10.1 | 500 | 1.00 | 26.1 | 140 | .0159 | 30.6 | 1440 | 940 | 77.5 |
| 159 | 10.0 | 500 | 1.00 | 26.1 | 141 | .0159 | 30.9 | 1425 | 925 | 75.9 |
| 42 | 10.0 | 500 | 1.01 | 26.2 | 143 | .0161 | 30.8 | 1415 | 915 | 75.2 |
| 36 | 10.2 | 502 | 1.00 | 28.3 | 139 | .0160 | 31.0 | 1530 | 1028 | 84.3 |
| 144 | 10.2 | 502 | 1.00 | 29.9 | 138 | .0159 | 30.8 | 1565 | 1063 | 87.9 |
| 33 | 10.3 | 501 | 1.02 | 30.6 | 138 | .0160 | 31.2 | 1555 | 1054 | 87.7 |
| 30 | 10.3 | 500 | 1.01 | 32.9 | 137 | .0160 | 31.2 | 1580 | 1080 | 89.3 |
| 27 | 10.3 | 503 | 1.00 | 36.0 | 136 | .0161 | 31.2 | 1612 | 1109 | 90.4 |
| 24 | 10.3 | 499 | 1.01 | 46.4 | 134 | .0161 | 31.7 | 1630 | 1131 | 92.8 |
| 124 | 14.3 | 503 | 1.02 | 18.7 | 102 | .0159 | 28.6 | 1193 | 690 | 57.3 |
| 129 | 14.4 | 502 | 1.00 | 18.7 | 99 | .0159 | 28.6 | 1240 | 738 | 60.1 |
| 125 | 14.3 | 502 | 1.00 | 19.2 | 100 | .0159 | 28.6 | 1313 | 811 | 66.2 |
| 128 | 14.3 | 500 | .99 | 20.1 | 99 | .0159 | 28.6 | 1435 | 935 | 76.9 |
| 123 | 14.3 | 499 | 1.00 | 20.9 | 99 | .0159 | 28.8 | 1498 | 999 | 82.7 |
| 116 | 14.4 | 500 | 1.00 | 20.9 | 99 | .0160 | 28.6 | 1513 | 1013 | 83.7 |
| 135 | 14.3 | 500 | 1.00 | 24.3 | 99 | .0159 | 28.8 | 1612 | 1112 | 92.7 |
| 170 | 14.3 | 500 | 1.01 | 24.3 | 99 | .0158 | 28.6 | 1595 | 1095 | 91.8 |
| 165 | 14.3 | 501 | 1.00 | 25.1 | 99 | .0158 | 28.3 | 1600 | 1099 | 92.0 |
| 140 | 14.4 | 501 | 1.00 | 26.1 | 98 | .0159 | 28.8 | 1643 | 1142 | 95.1 |
| 158 | 14.3 | 500 | 1.00 | 26.1 | 98 | .0159 | 28.8 | 1623 | 1123 | 93.0 |
| 137 | 14.4 | 502 | 1.01 | 28.2 | 99 | .0159 | 28.8 | 1642 | 1140 | 95.6 |
| 111 | 14.4 | 500 | 1.00 | 30.2 | 97 | .0160 | 28.8 | 1645 | 1145 | 94.5 |
| 108 | 14.3 | 505 | 1.00 | 32.2 | 99 | .0160 | 29.1 | 1643 | 1138 | 94.0 |
| 80 | 21.3 | 505 | 1.00 | 16.2 | 68 | .0161 | 25.4 | 1328 | 823 | 66.7 |
| 82 | 21.5 | 505 | 1.00 | 17.2 | 67 | .0161 | 25.3 | 1528 | 1023 | 84.5 |
| 63 | 21.4 | 503 | 1.00 | 18.2 | 67 | .0160 | 25.8 | 1615 | 1112 | 92.2 |
| 92 | 21.3 | 500 | 1.01 | 18.2 | 67 | .0161 | 25.8 | 1605 | 1105 | 91.6 |
| 55 | 21.4 | 503 | 1.02 | 20.1 | 68 | .0161 | 25.6 | 1625 | 1122 | 94.5 |
| 51 | 21.4 | 502 | 1.00 | 20.9 | 67 | .0161 | 25.8 | 1650 | 1148 | 94.5 |
| 67 | 21.5 | 497 | 1.00 | 20.9 | 66 | .0160 | 25.2 | 1635 | 1138 | 94.4 |
| 89 | 21.4 | 502 | 1.00 | 20.9 | 67 | .0161 | 25.8 | 1647 | 1145 | 94.2 |
| 45 | 21.4 | 502 | 1.01 | 26.4 | 67 | .0161 | 26.2 | 1645 | 1143 | 95.3 |
| 102 | 30.1 | 504 | .99 | 15.8 | 47 | .0159 | 21.5 | 1570 | 1066 | 88.3 |
| 101 | 30.0 | 504 | 1.00 | 15.9 | 48 | .0159 | 22.0 | 1560 | 1056 | 88.5 |
| 79 | 30.0 | 505 | 1.00 | 16.2 | 48 | .0162 | 21.6 | 1569 | 1064 | 87.1 |
| 81 | 30.0 | 505 | 1.00 | 17.2 | 48 | .0161 | 21.1 | 1645 | 1140 | 94.3 |
| 95 | 30.0 | 502 | 1.01 | 18.1 | 48 | .0161 | 21.7 | 1652 | 1150 | 95.8 |
| 56 | 30.1 | 504 | 1.02 | 20.0 | 49 | .0160 | 21.5 | 1668 | 1164 | 98.4 |
| 68 | 30.1 | 497 | 1.00 | 20.9 | 47 | .0160 | 21.2 | 1675 | 1178 | 97.8 |
| 17 | 29.9 | 502 | 1.00 | 20.9 | 48 | .0160 | 21.5 | 1675 | 1173 | 97.8 |

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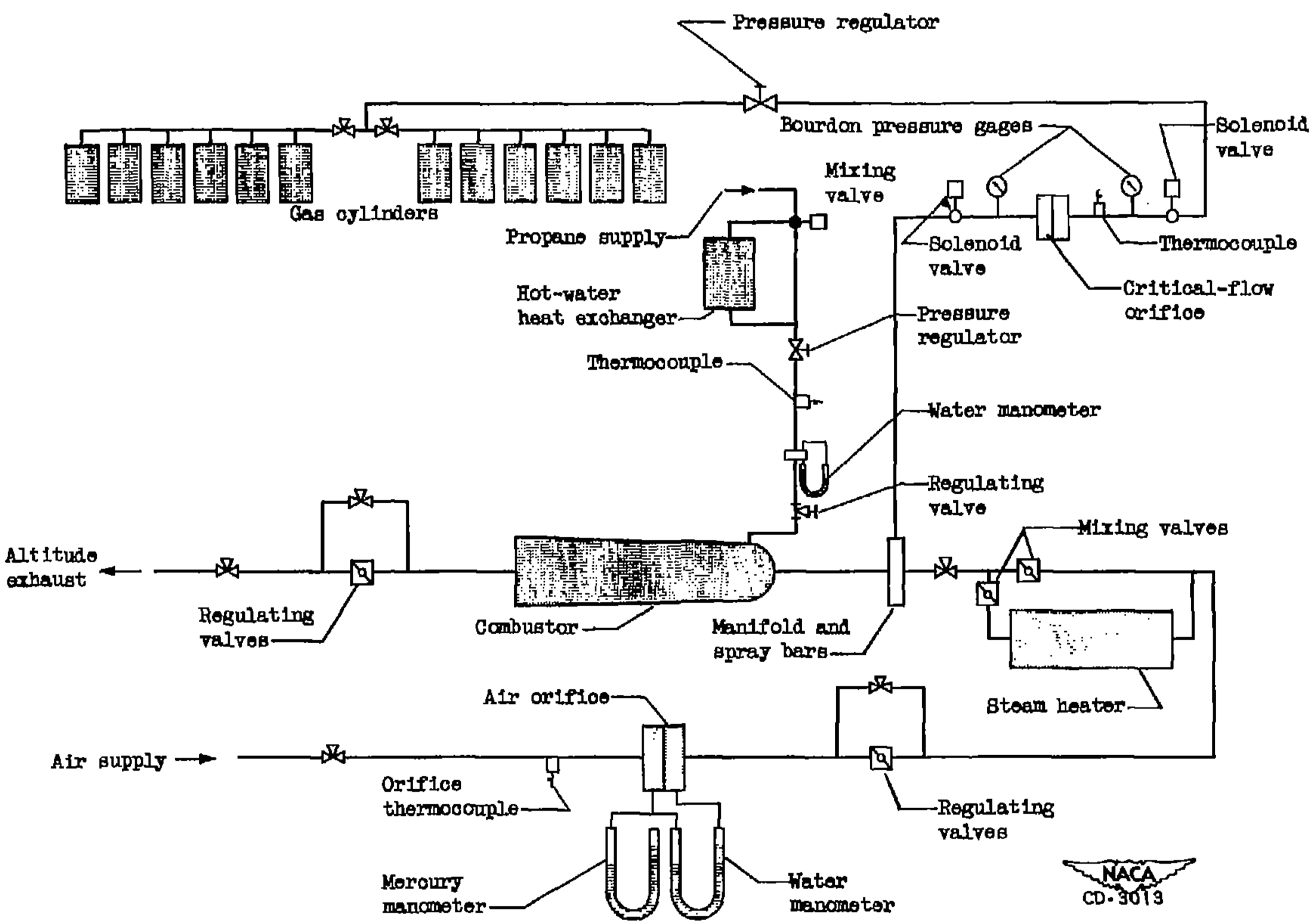



Figure 1. - Schematic sketch of J33-combustor experimental apparatus.

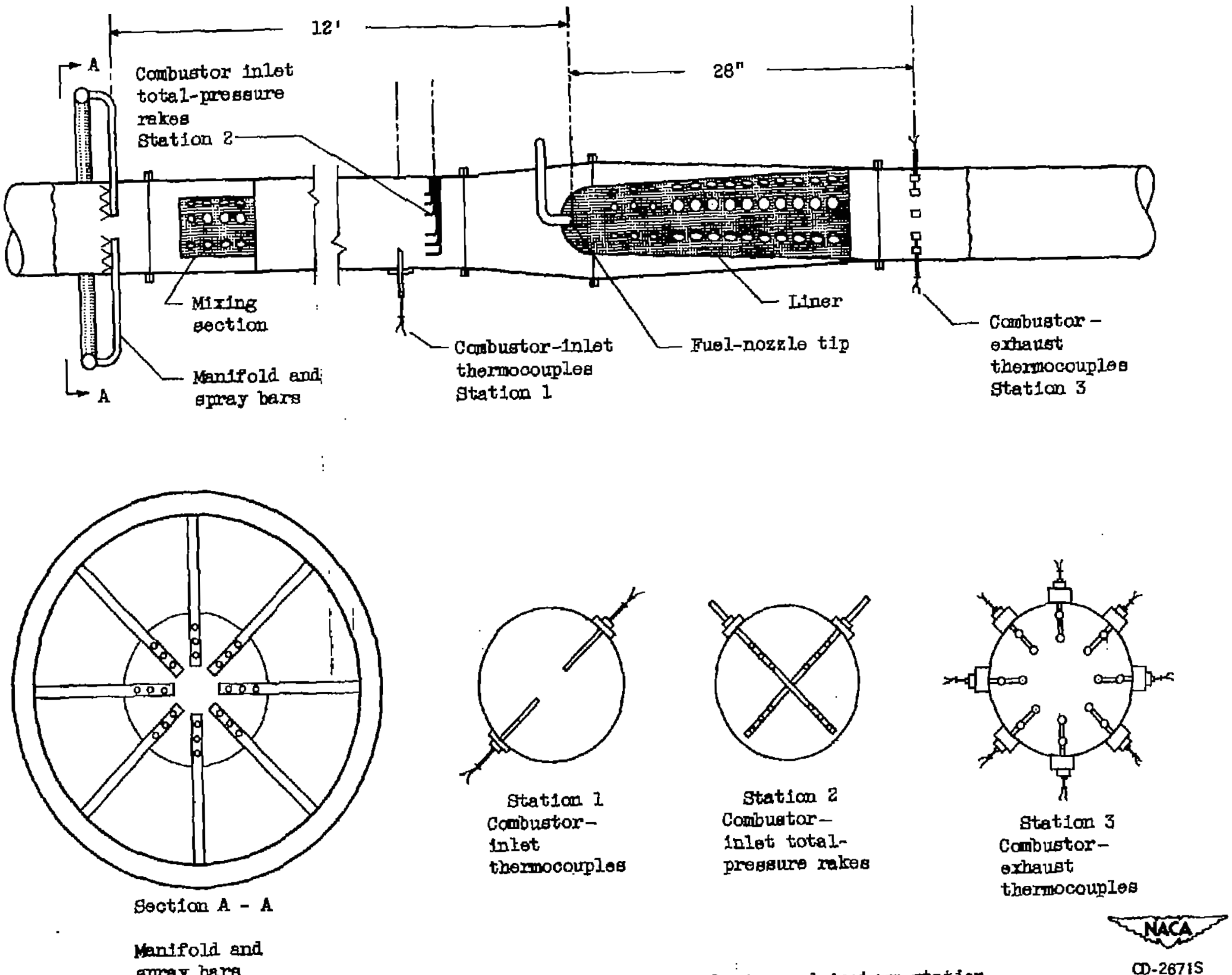
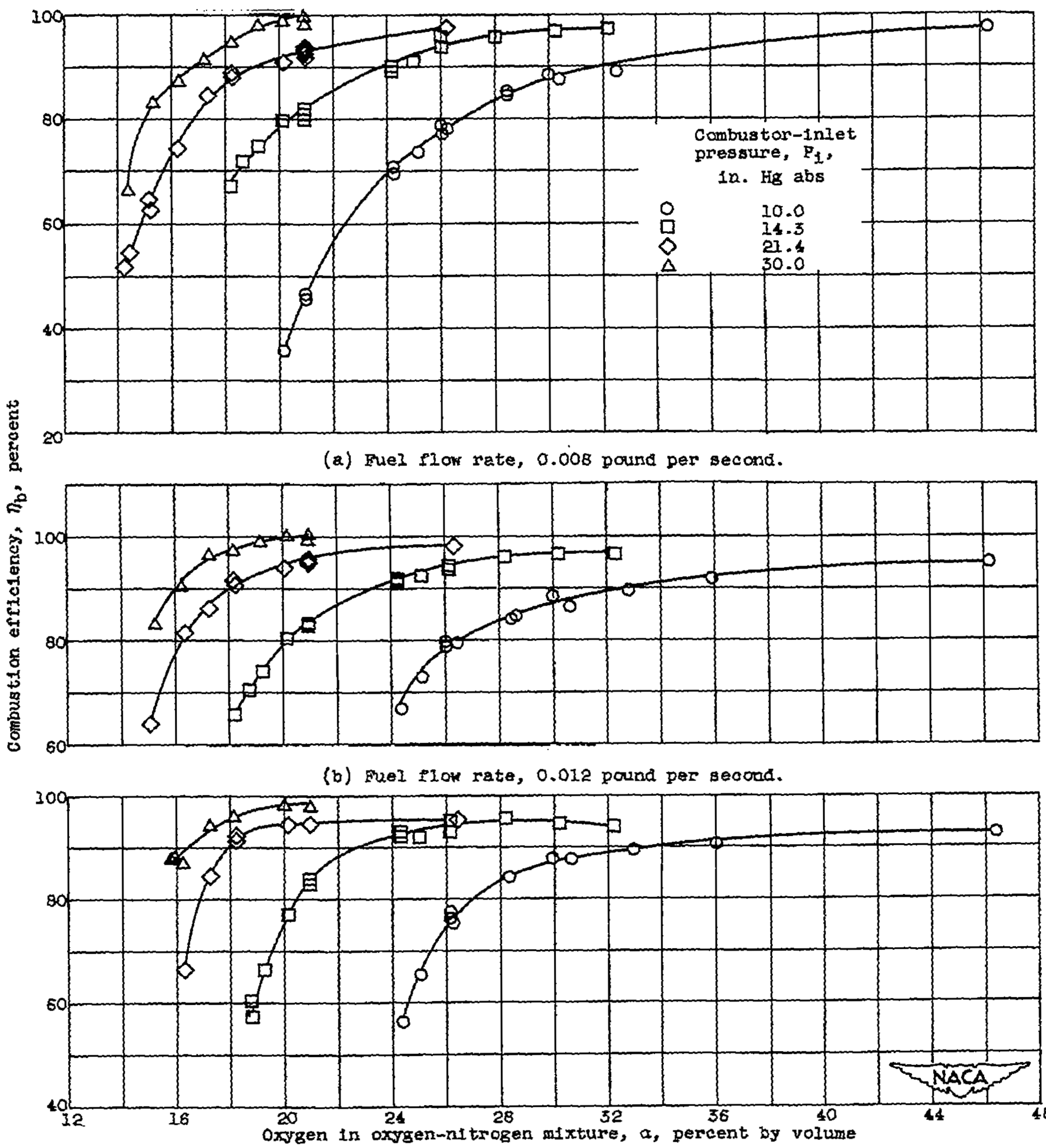



Figure 2. - Sketch of single J33 combustor and instrumentation.




(c) Fuel flow rate, 0.016 pound per second.

Figure 3. - Effect of oxygen concentration of inlet oxygen-nitrogen mixture on combustion efficiency of single J33 combustor over a range of inlet pressures and fuel flow rates. Fuel, propane; combustor-inlet temperature, 40° F; weight flow rate of inlet oxygen-nitrogen mixture, 1.0 pound per second.

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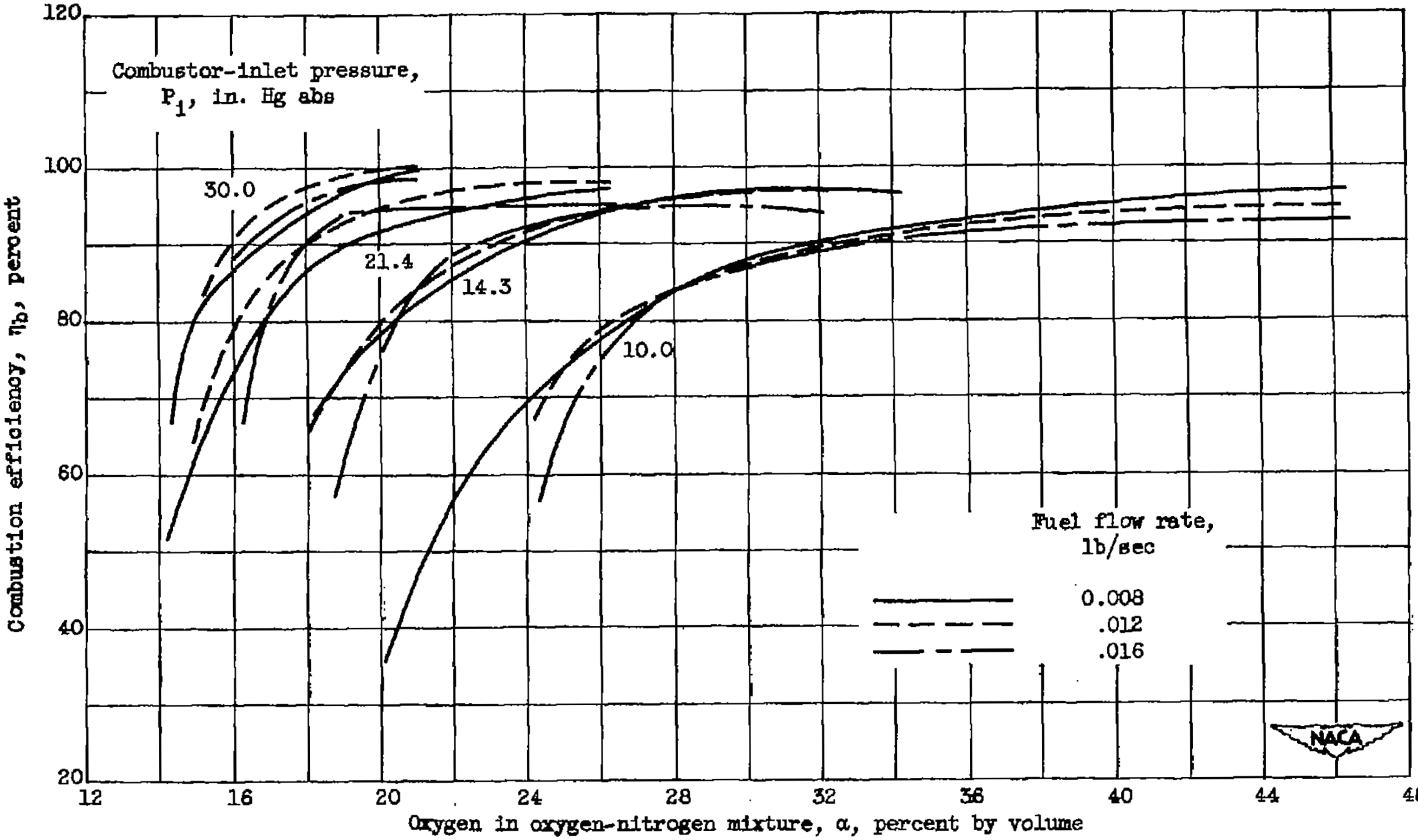
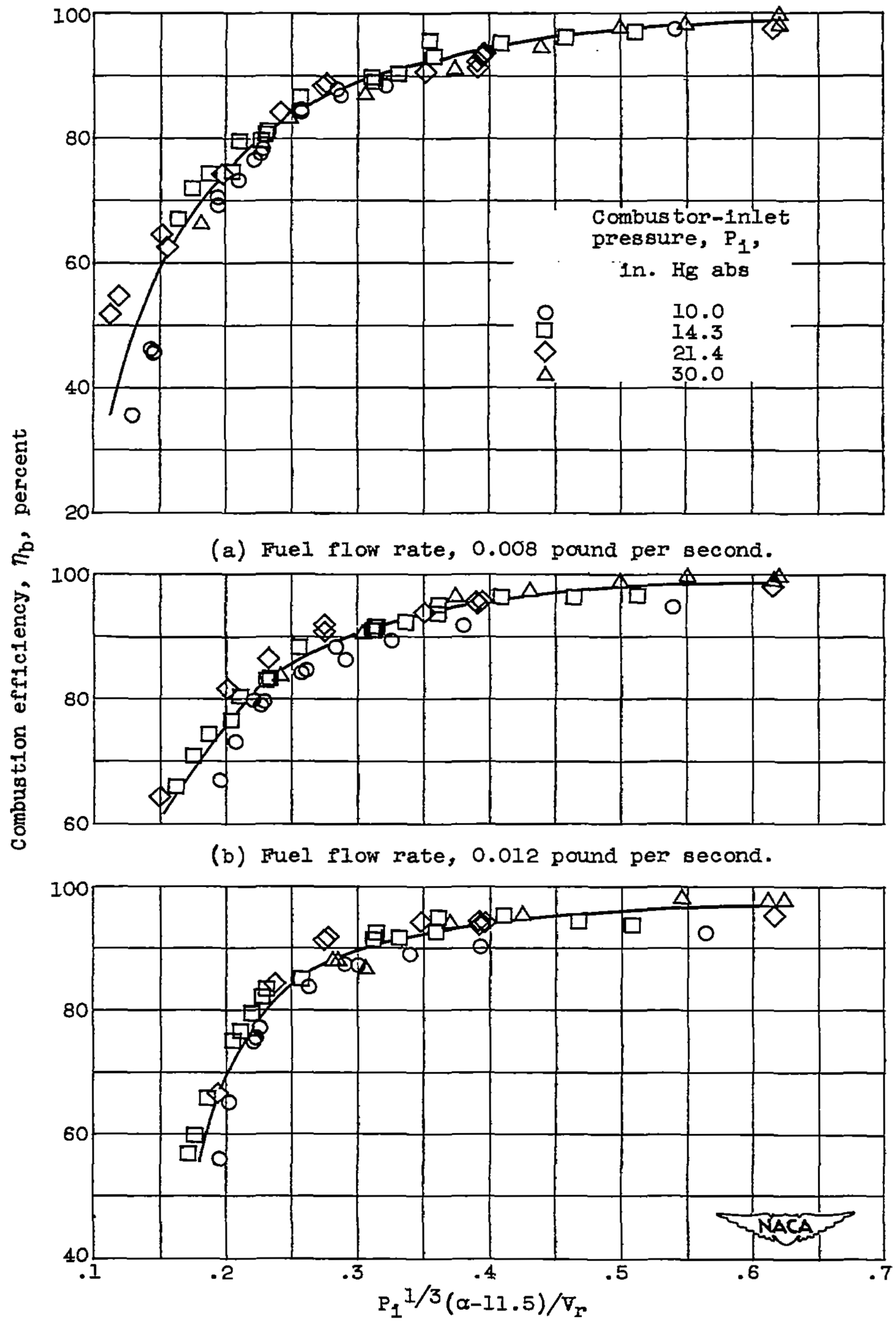
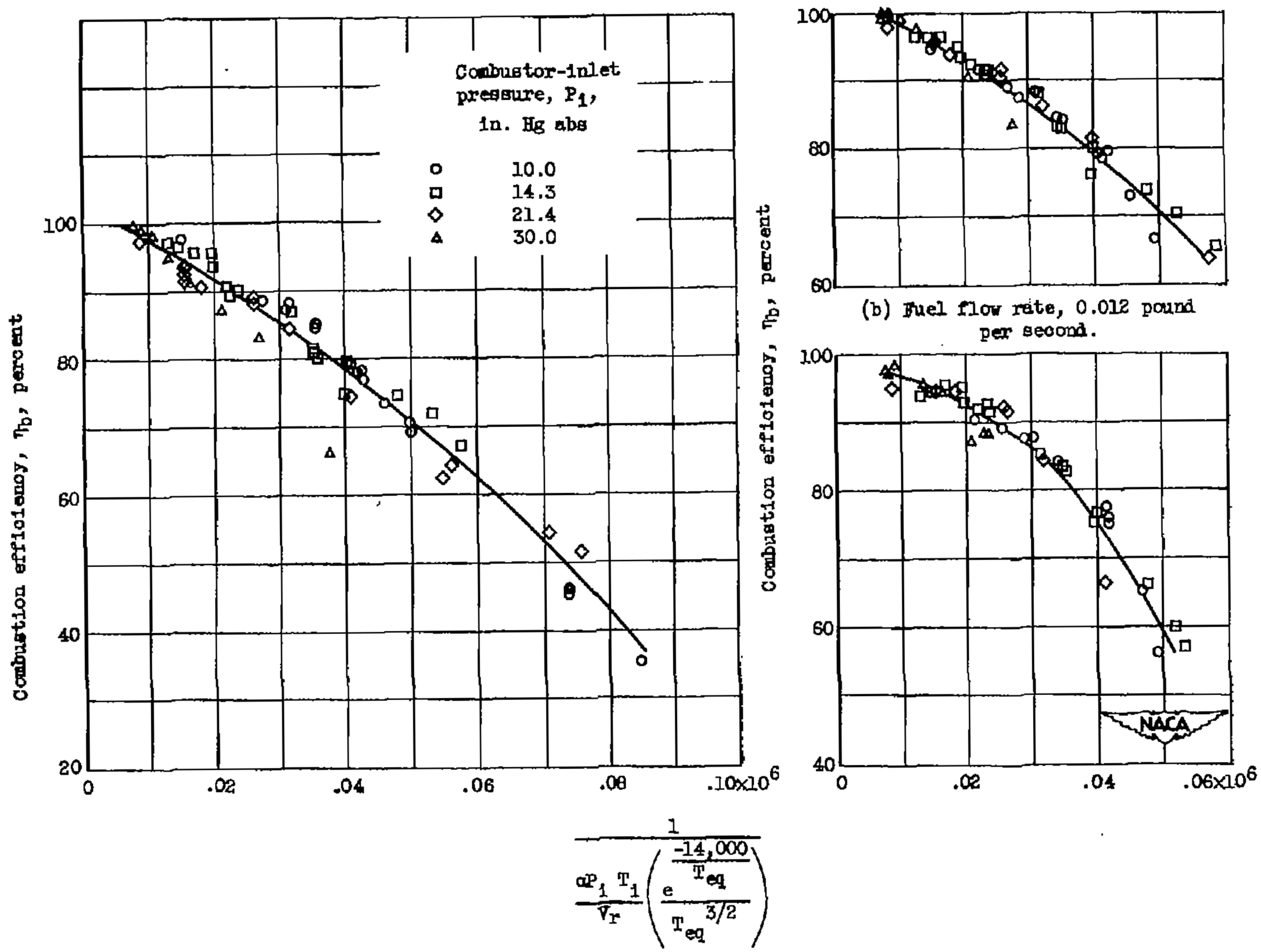



Figure 4. - Effect of fuel flow rate on combustion efficiency of J33 combustor over a range of inlet pressures and oxygen concentrations. Fuel, propane; combustor-inlet temperature, 40° F; weight flow rate of inlet oxygen-nitrogen mixture, 1.0 pound per second.




(c) Fuel flow rate, 0.016 pound per second.

Figure 5. - Correlation of combustion efficiency of single J33 combustor with flame speed parameter. Fuel, propane; combustor-inlet temperature, 40° F; weight flow rate of inlet oxygen-nitrogen mixture, 1.0 pound per second.

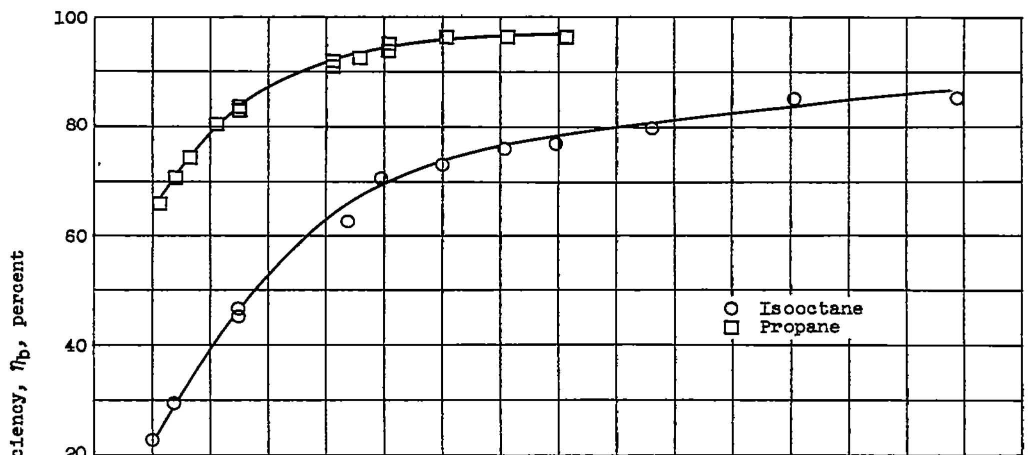



(a) Fuel-flow rate, 0.008 pound per second.

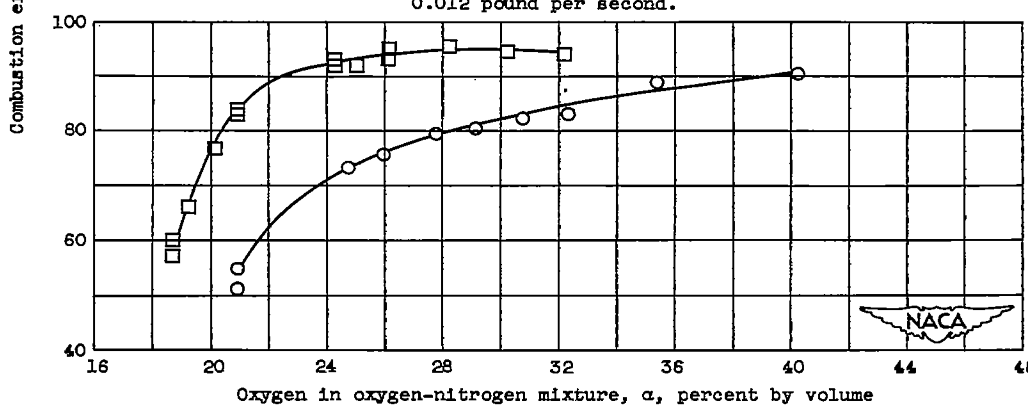
(b) Fuel flow rate, 0.012 pound per second.

(c) Fuel flow rate, 0.016 pound per second.

Figure 6. - Correlation of combustion efficiency of single J33 combustor with reciprocal of second-order reaction equation parameter. Fuel, propane; combustor-inlet temperature, 40° F; weight flow rate of inlet oxygen-nitrogen mixture, 1.0 pound per second.

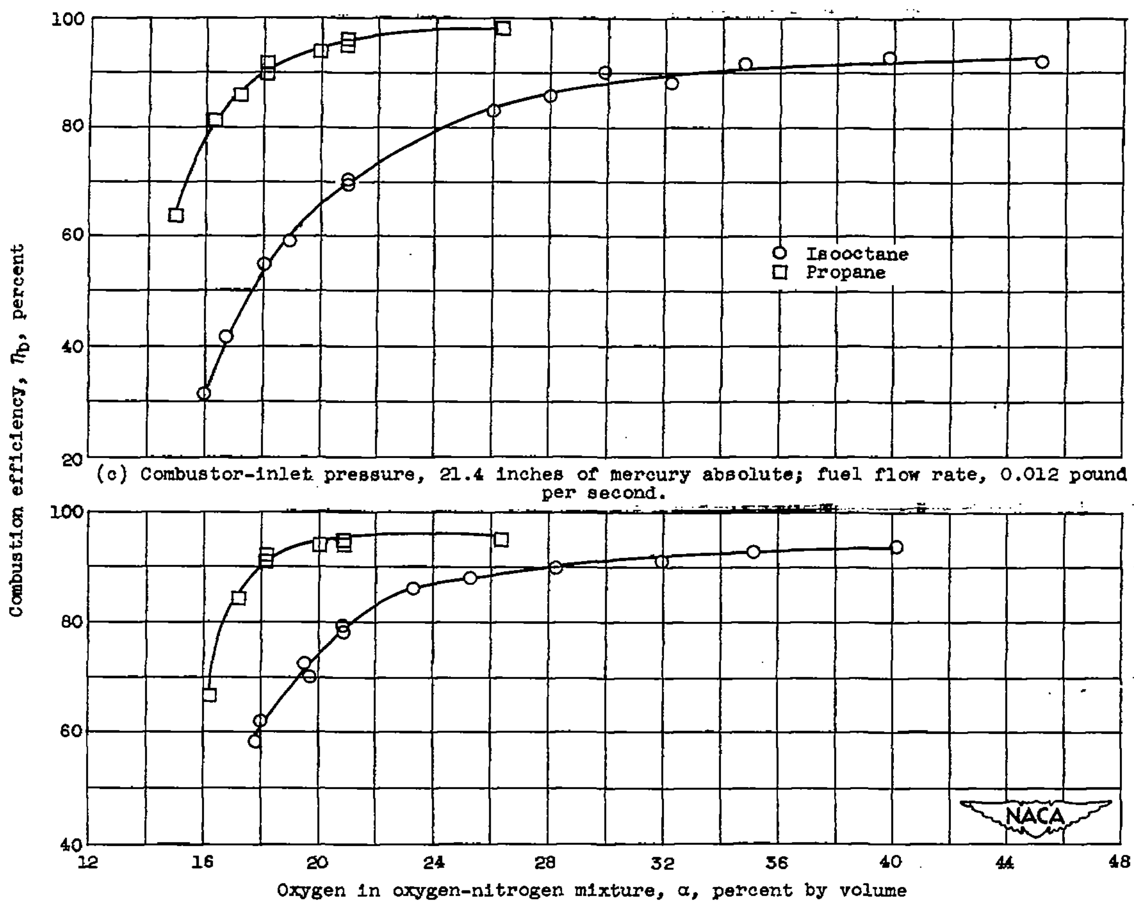



(a) Combustor-inlet pressure, 14.3 inches of mercury absolute; fuel flow rate, 0.012 pound per second.




(b) Combustor-inlet pressure, 14.3 inches of mercury absolute; fuel flow rate, 0.016 pound per second.

Figure 7. - Comparison of combustion efficiency of single J33 combustor operating with propane and isooctane fuels. Combustor-inlet temperature, 40° F; weight flow rate of inlet oxygen-nitrogen mixture, 1.0 pound per second.




(c) Combustor-inlet pressure, 21.4 inches of mercury absolute; fuel flow rate, 0.012 pound per second.

(d) Combustor-inlet pressure, 21.4 inches of mercury absolute; fuel flow rate, 0.016 pound per second.

Figure 7. - Concluded. Comparison of combustion efficiency of single J33 combustor operating with propane and isooctane fuels. Combustor-inlet temperature, 40° F; weight flow rate of inlet oxygen-nitrogen mixture, 1.0 pound per second.



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